The Observation of B^0_s Oscillations at the Tevatron

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Fermion Masses

- Gauge sector with massless fermions:

$$\mathcal{L}_F = \sum_{\psi_L} \overline{\psi}_L i \not{D} \psi_L + \sum_{\psi_L} \overline{\psi}_R i \not{D} \psi_R$$

- Higgs sector:

$$\mathcal{L}_H = (D^\mu \Phi)^* D_\mu \Phi - V(\Phi)$$

- General Higgs-quark couplings:

$$-\mathcal{L}_{HF} = \mathbf{f}_u \overline{\mathbf{q}}'_L \tilde{\Phi} \mathbf{u}'_R + \mathbf{f}_d \overline{\mathbf{q}}'_L \Phi \mathbf{d}'_R + h.c.$$

- Spontaneous symmetry breaking:

$$\mathbf{m}'_q = \frac{v}{\sqrt{2}} \mathbf{f_q} \quad \xRightarrow[\text{diagonalize}]{} \quad \mathbf{m} = \mathbf{S}_L^\dagger \mathbf{m}' \mathbf{S}_R$$

CKM Sector of the Standard Model

$$\mathbf{V}_{CKM} = \mathbf{S}^{\dagger}_{u,L}\mathbf{S}_{d,L}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

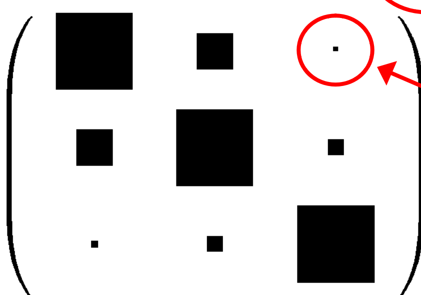
- One of several explanations for CP violation observed in $K_L^0 \rightarrow \pi^+\pi^-$
- If this was the source of CP violation in the kaon system, then *large* effects should be observed in B decays.

The CKM Matrix

- Unitary 3x3 matrix → 4 parameters:

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$|V_{CKM}| \sim$$



Magnitude proportional to the *area* of this little square...

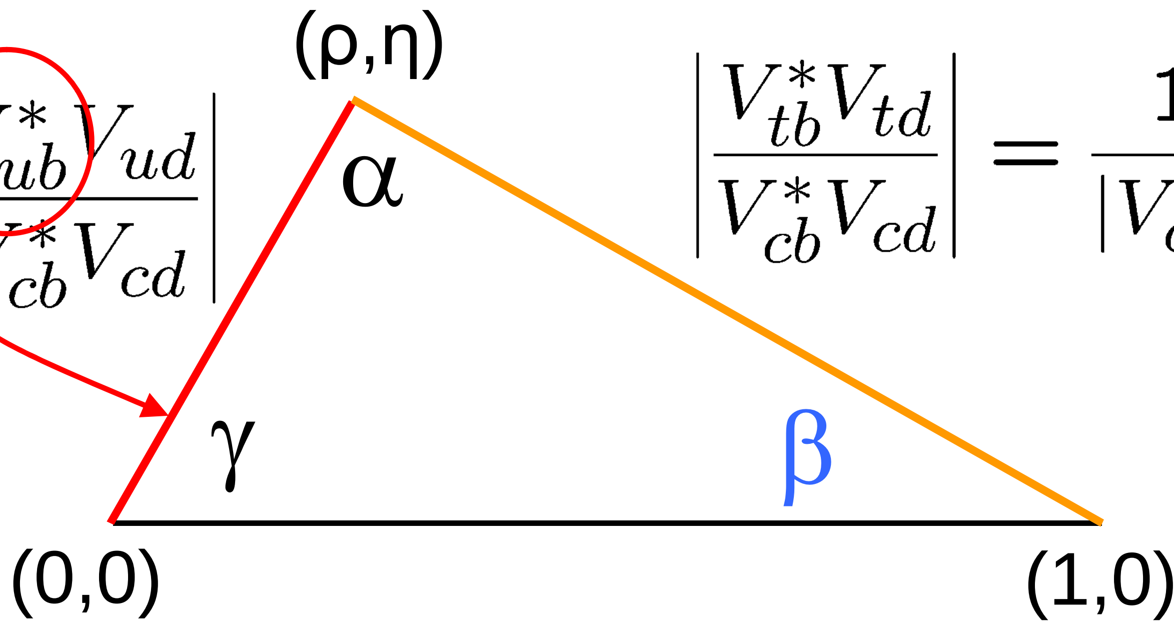
- $\lambda = 0.2272 \pm 0.0010$
  $A = 0.809 \pm 0.014$

Already well measured

(most recent results from CKMFitter)

- CP violation → $\eta \neq 0$
- Need a *precise* determination of V_{td}

The Unitary Triangle



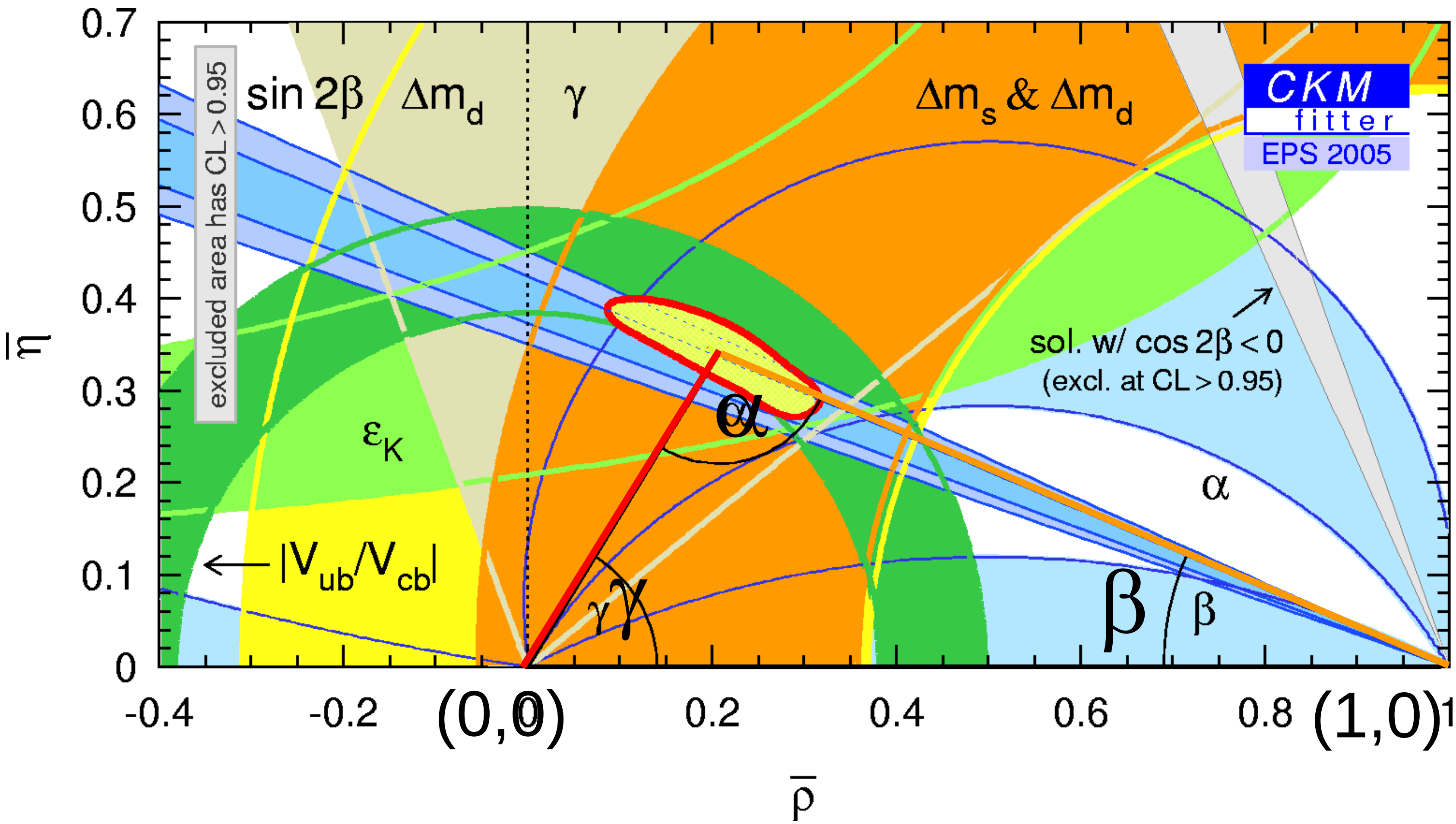
$$\left|\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}\right|$$

$$\left|\frac{V_{tb}^{*}V_{td}}{V_{cb}^{*}V_{cd}}\right| = \frac{1}{|V_{cd}|}\frac{|V_{td}|}{|V_{ts}|}$$

$$\frac{|V_{td}|^2}{|V_{ts}|^2} \sim \frac{\Delta m_d}{\Delta m_s}$$

- Try to over-constrain its shape:
  - A_{CP} in $B^0 \rightarrow J/\psi K^0_S$: sin 2β=0.72±0.02
  - Length of one side from $b \longrightarrow u\ell\overline{\nu}_\ell$
  - Length of other side from $\Delta m_d/\Delta m_s$...

Last Year's Unitary Triangle



- Next strong constraint will come from Δm_s.

B_d^0/B_s^0 Mixing

- Quark flavor eigenstates:

$$B_d^0 = (\bar{b}d) \qquad B_s^0 = (\bar{b}s)$$
$$\overline{B}_d^0 = (b\bar{d}) \qquad \overline{B}_s^0 = (b\bar{s})$$

- Time dependence:

$$i\hbar\frac{d}{dt}\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix} = \begin{pmatrix} M & \delta \\ \delta & M \end{pmatrix}\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix}$$

- CP eigenstates:

$$|B_H\rangle \sim |B^0\rangle - |\overline{B}^0\rangle, M_H = M + \delta$$
$$|B_L\rangle \sim |B^0\rangle + |\overline{B}^0\rangle, M_L = M - \delta$$

- Mass difference: $\Delta m = M_H - M_L$

Time Evolution

- QCD produces flavor eigenstates:

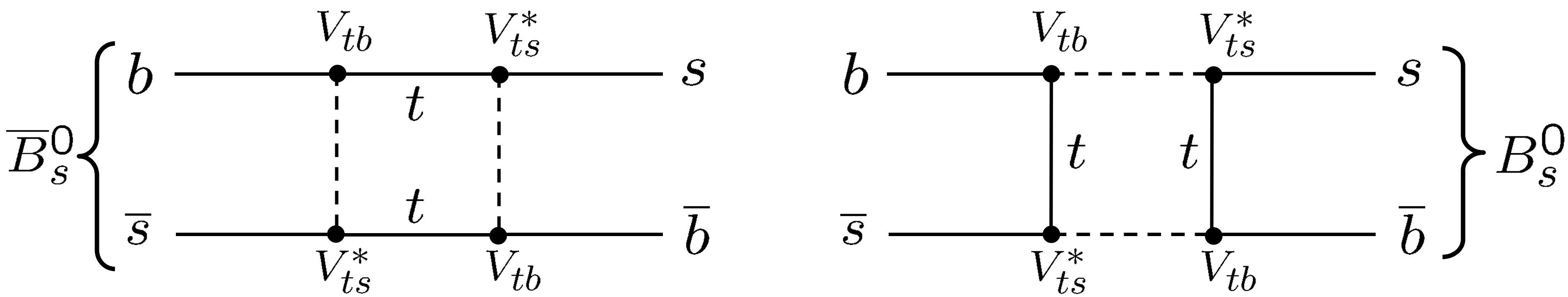
$$|B^0\rangle \sim |B_H\rangle + |B_L\rangle$$
$$|\overline{B}^0\rangle \sim |B_H\rangle - |B_L\rangle$$

- Interference between CP eigenstates
- Decay identifies final quark flavor:

$$\mathcal{P}_{\mathsf{same/opposite}}(t) = \frac{e^{-\Gamma t}}{2\Gamma}(1 \pm \cos \Delta m t)$$

- Fit for Δm_s using this model, taking into account several experimental limitations.

B_d^0/B_s^0 Mixing



$$\Delta m_s \sim m_{B_s} f_{B_s}^2 B_{B_s} |V_{tb} V_{ts}^*|^2$$

$$\Delta m_d \sim m_{B_d} f_{B_d}^2 B_{B_d} |V_{tb} V_{td}^*|^2$$

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

Δm_d and masses are well measured

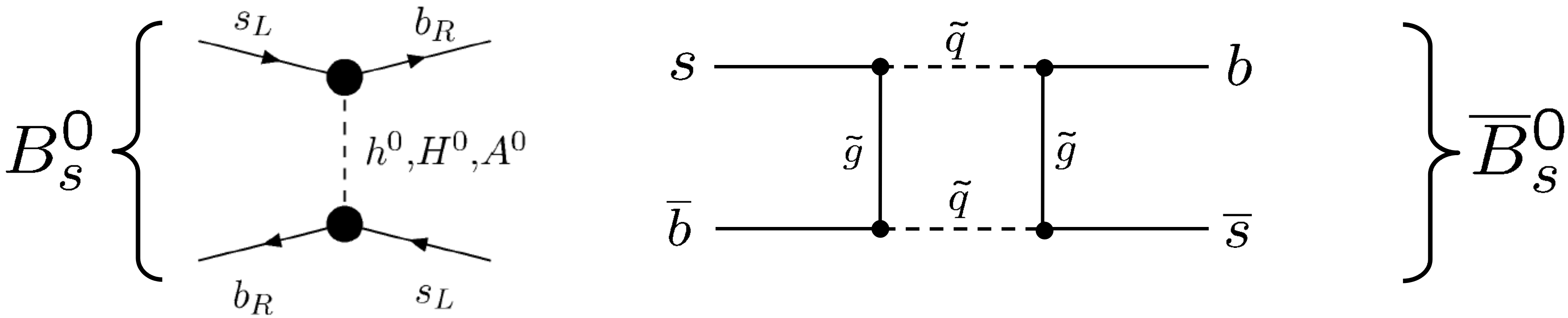
$$\xi = \frac{f_{B_s}}{f_{B_d}} \sqrt{\frac{B_{B_s}}{B_{B_d}}} = 1.210^{+0.047}_{-0.035}$$

From lattice QCD

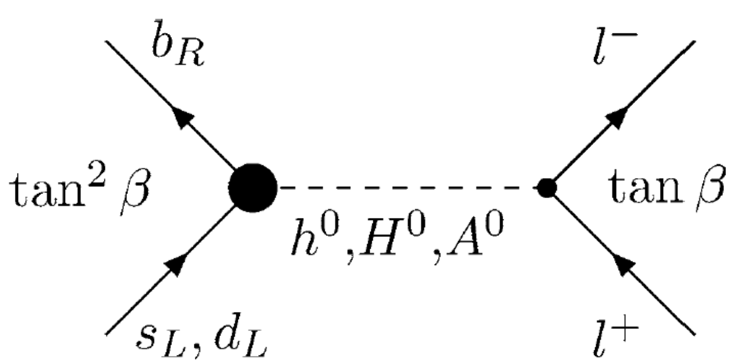
(hep-lat/0510113)

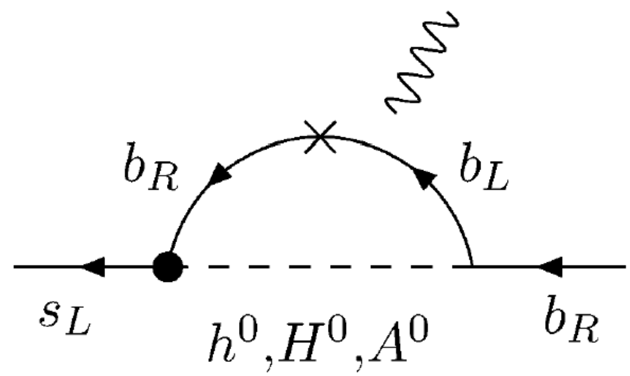
Contributions from New Physics?

- FCNC suppressed in Standard Model
- Contribution from new physics scenarios:



- Also affects $B_s^0 \to \mu^+\mu^-, B \to X_s\gamma, \delta a_\mu, \ldots$





Search for B_s Oscillations

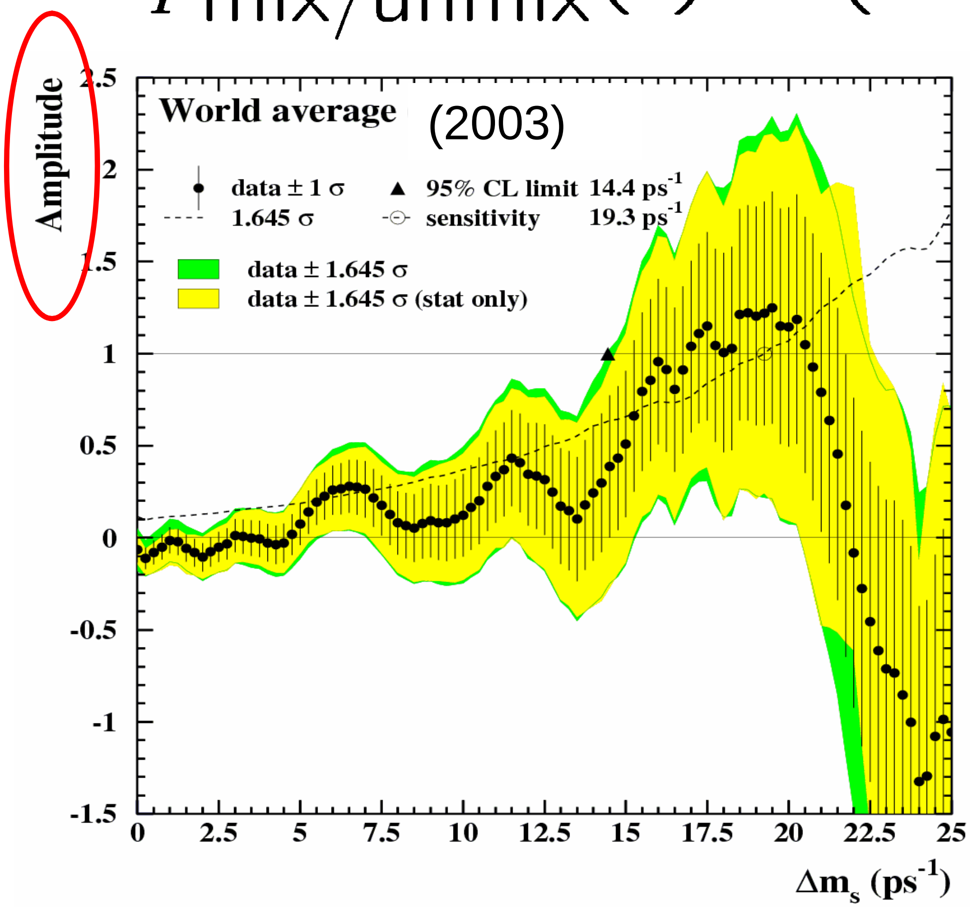
- Four steps:
  - Reconstruct B_s^0 decays
  - Measure proper decay time *precisely*
  - Identify initial flavor state $(B_s^0 \text{ or } \overline{B}_s^0?)$

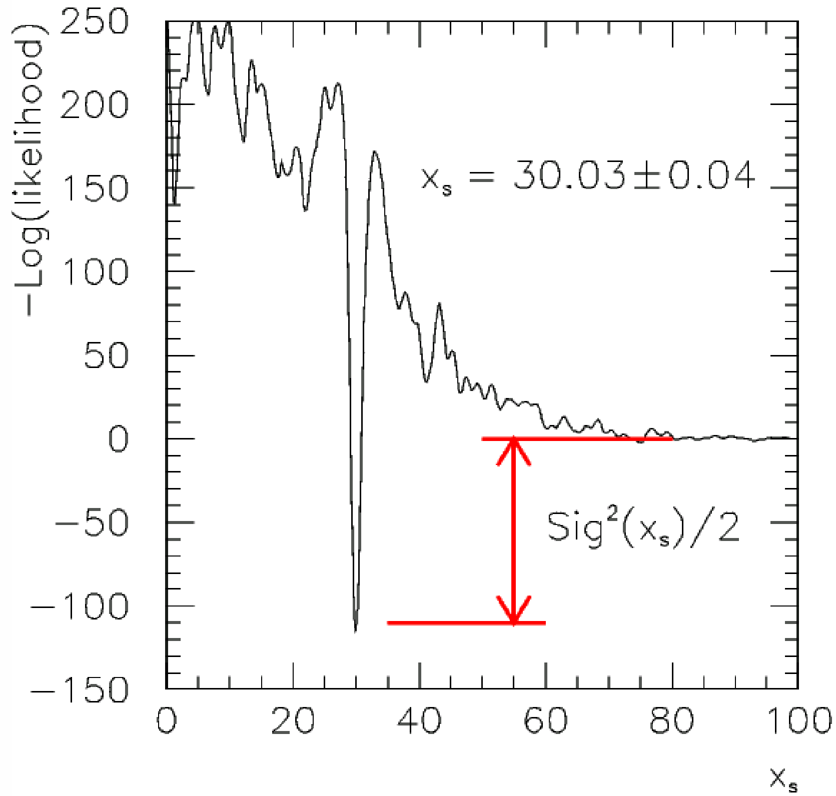
    Statistical power reduced by efficiency and mistag fraction (εD^2)
  - Is the data consistent with oscillations at a given mixing frequency?
- Significance of an observation:

$$\mathcal{S}\text{ig}(\Delta m_s) = \sqrt{\frac{S}{S+B}}\sqrt{\frac{S\epsilon D^2}{2}}e^{-\sigma_{ct}^2 \Delta m_s^2/2}$$

Amplitude Scans and Likelihood

$$p_{\mathrm{mix/unmix}}(t) \sim (1 \pm \mathcal{A}\,\mathcal{D}_{\mathrm{tag}} \cos \Delta m_s t)$$

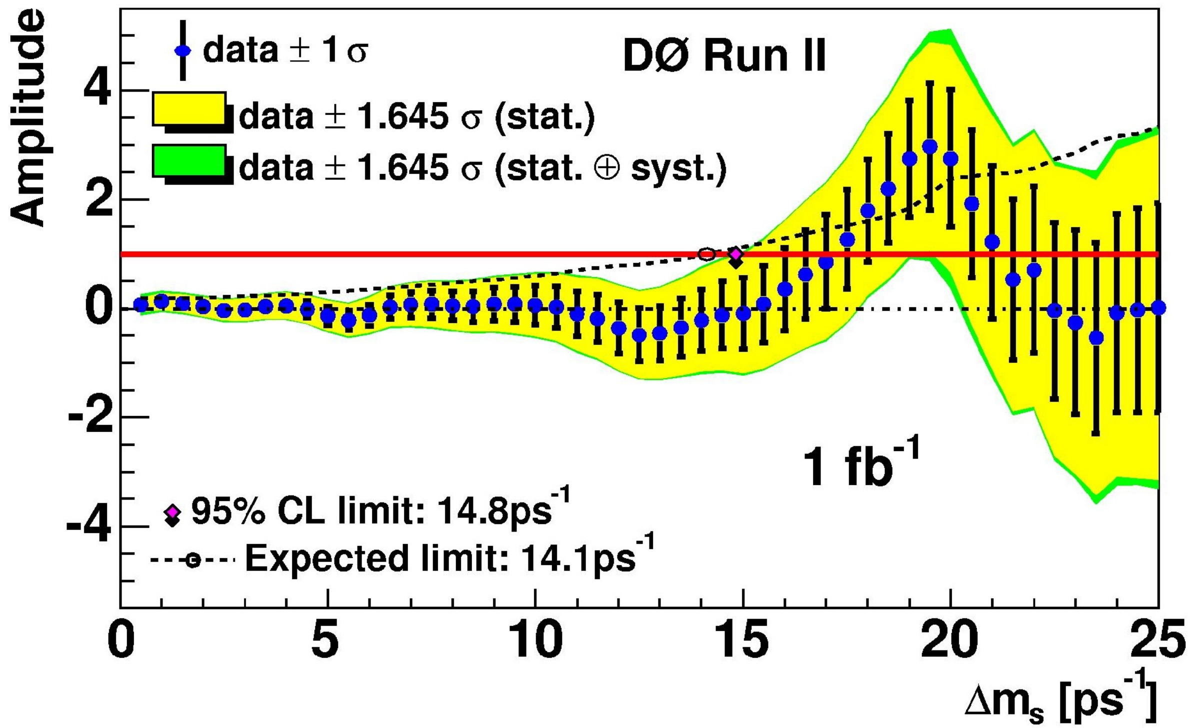




Expect A=1 at true Δm_s

Significance from depth of log-likelihood ratio

Result from the DØ Experiment



- March 12, Moriond EW 2006
- Result from DØ: $17<\Delta m_s<21$ ps^{-1} (90% CL)

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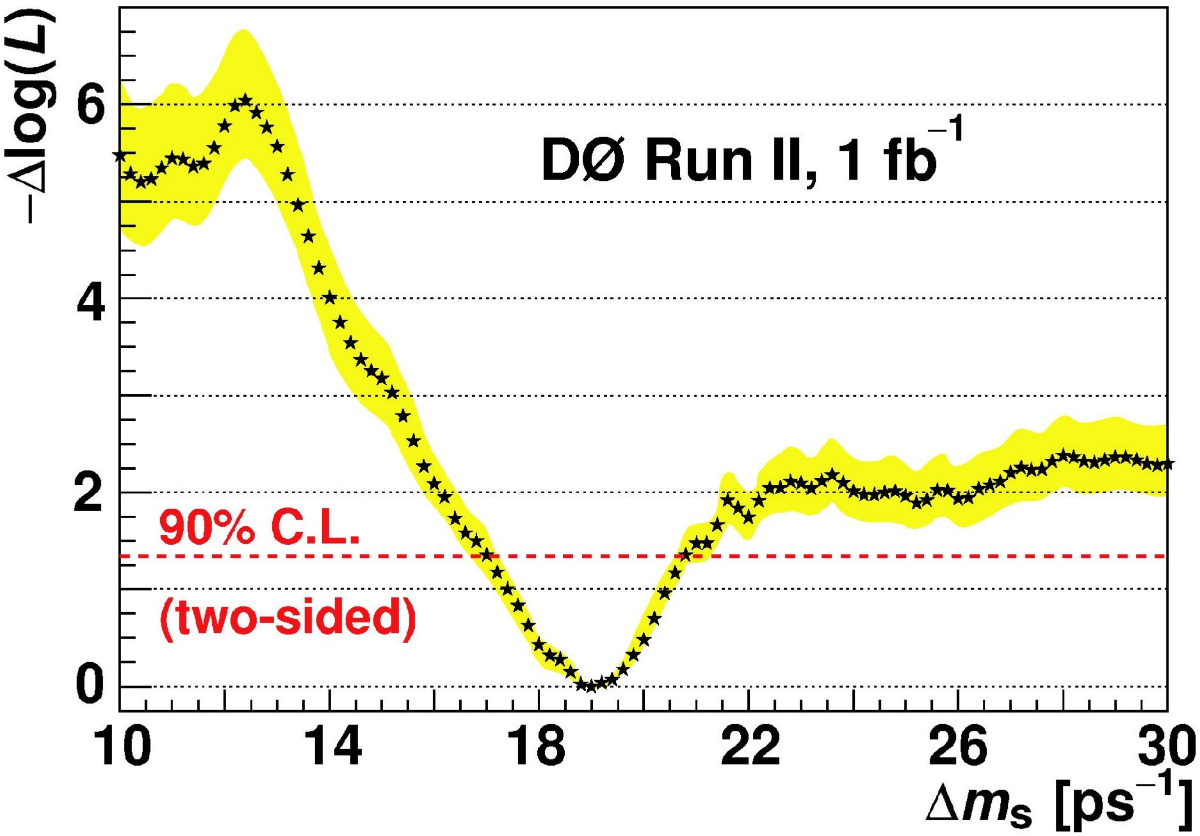

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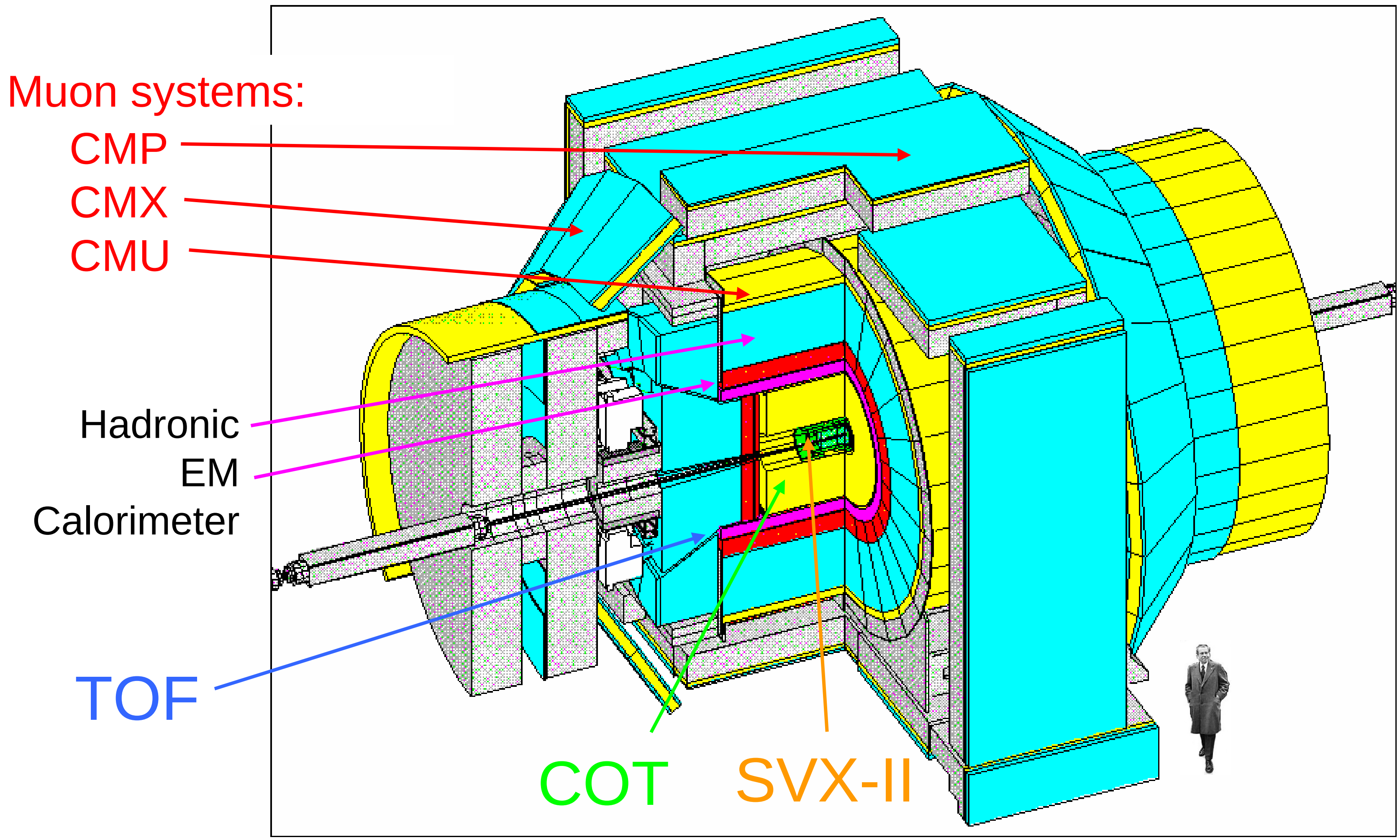
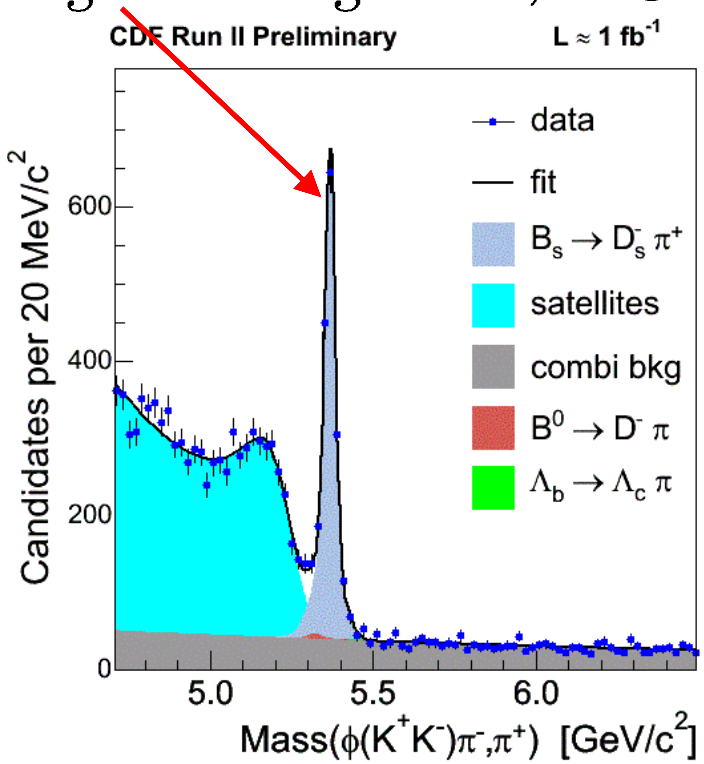
The CDF Detector



Signal Reconstruction

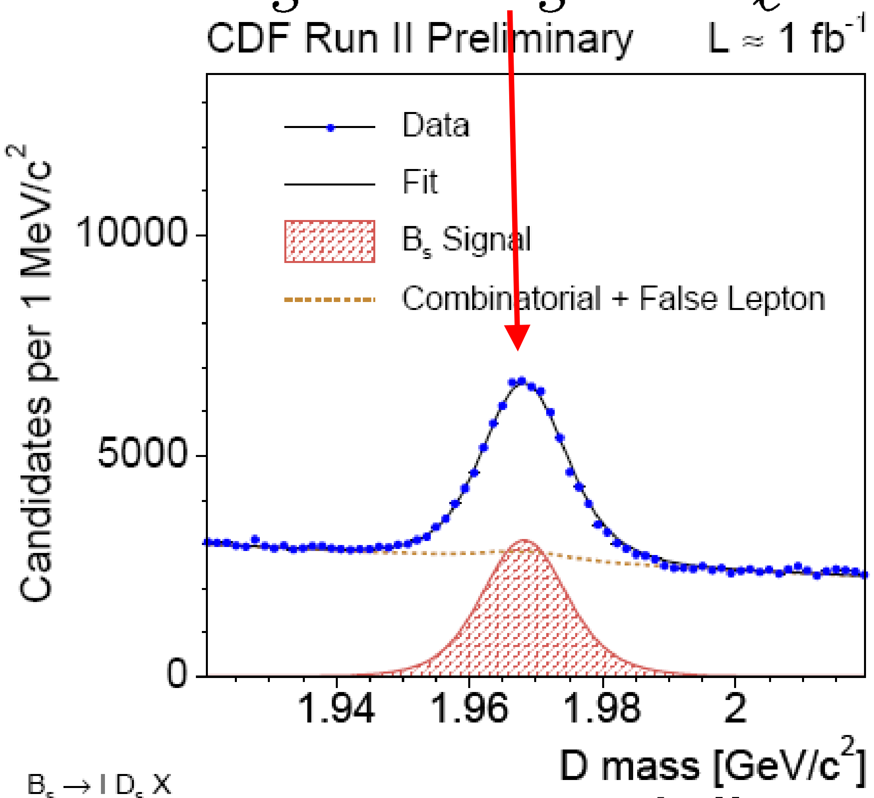
- Trigger on displaced tracks and look for:

$B_s^0 \to D_s^- \pi^+, D_s 3\pi$



3,700 fully reconstructed

$B_s^0 \to D_s^- \ell^+ \nu_\ell X$



53,000 partially reconstructed

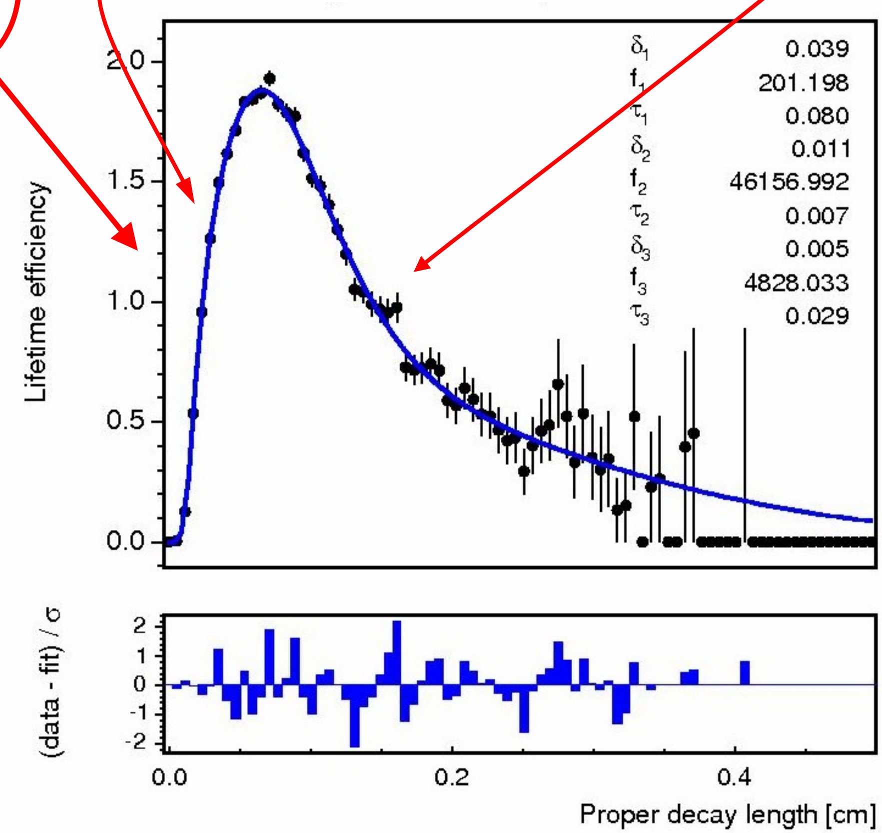
Proper Decay Time

- Proper decay time: $ct = L_{xy}\, M/p_T$
- Impact parameter trigger → lifetime bias

$$p(t;\tau) = \left(\underbrace{\frac{e^{-t/\tau}}{\tau}}_{\text{lifetime}} * \underbrace{R(t)}_{\text{resolution}} \right) \epsilon(t)$$

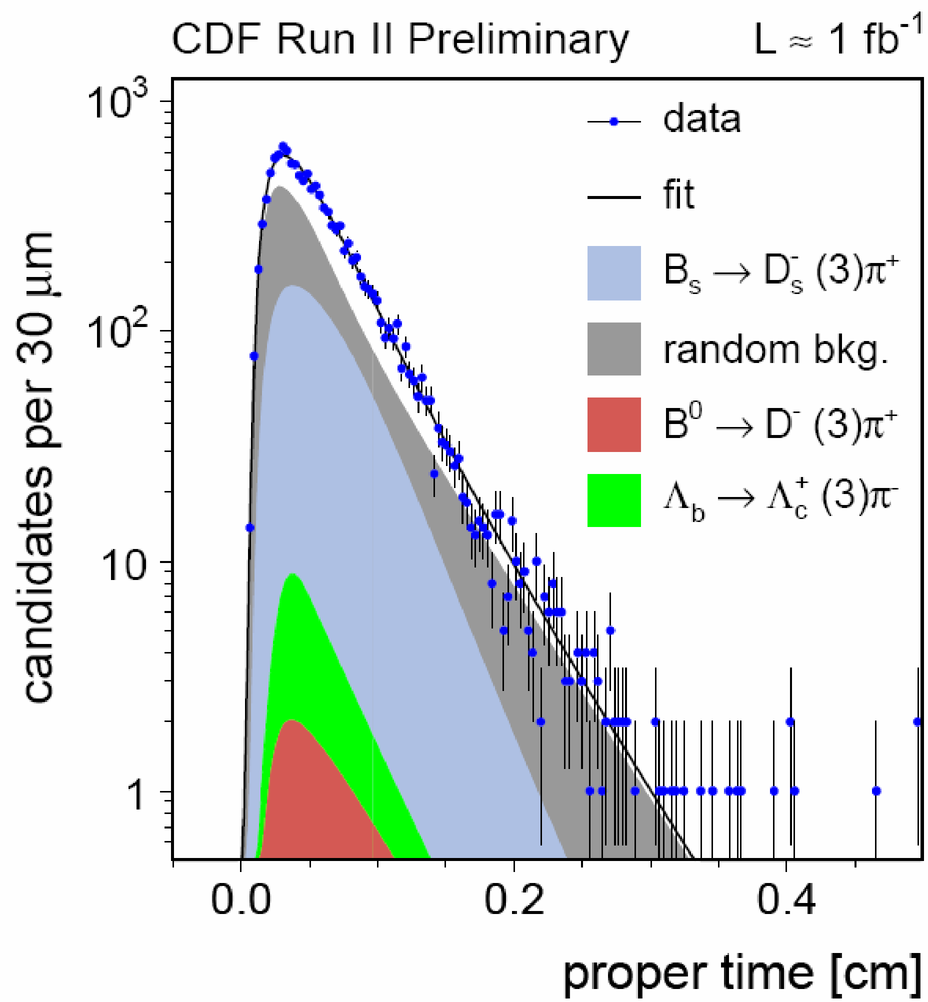
Limited number of patterns

Cut at $|d_0|>120$ μm



- Efficiency calculated using B Monte Carlo and an emulation of the trigger
- Checked using $B^+ \to J/\psi K^+$

Lifetime Measurements



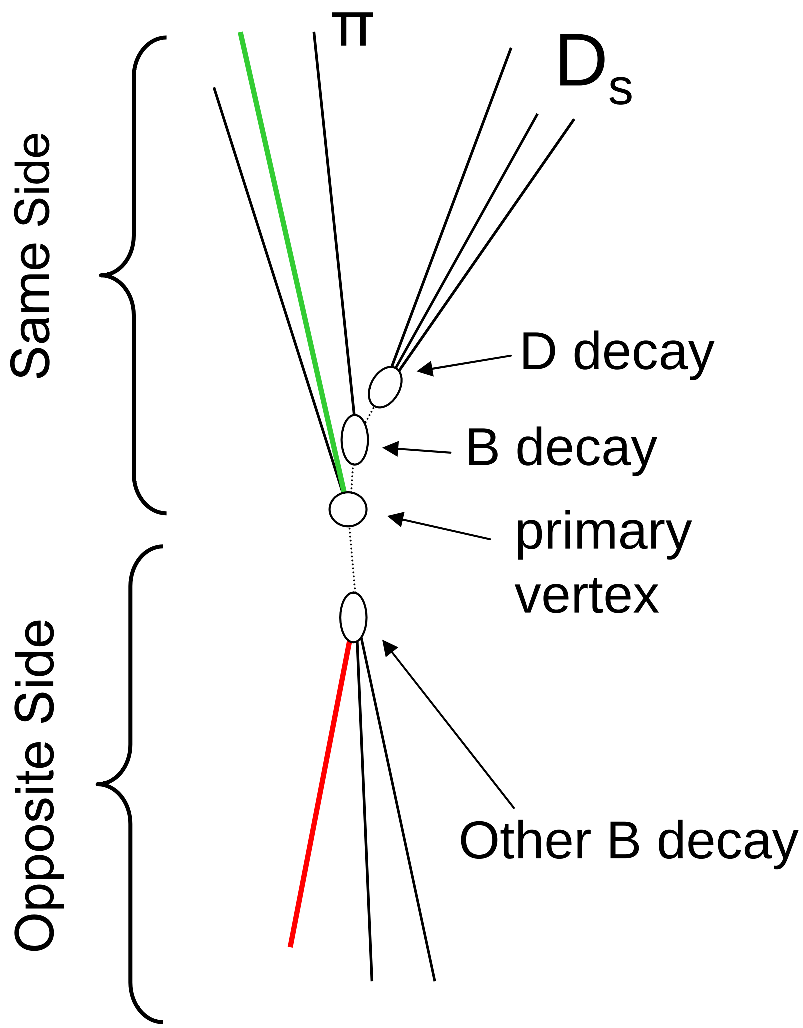
Decay	Lifetime (ps)
$B^0 \to D^-\pi^+$	1.508 ± 0.017
$B^- \to D^0\pi^-$	1.638 ± 0.017
$B_s^0 \to D_s(3)\pi$	1.538 ± 0.040

Still dominated by statistical uncertainty

World Averages: hep-ex/0603003

Decay	Lifetime (ps)
$\tau(B^0)$	1.527 ± 0.008
$\tau(B^+)$	1.643 ± 0.010
$\tau(B_s^0)$	1.454 ± 0.040

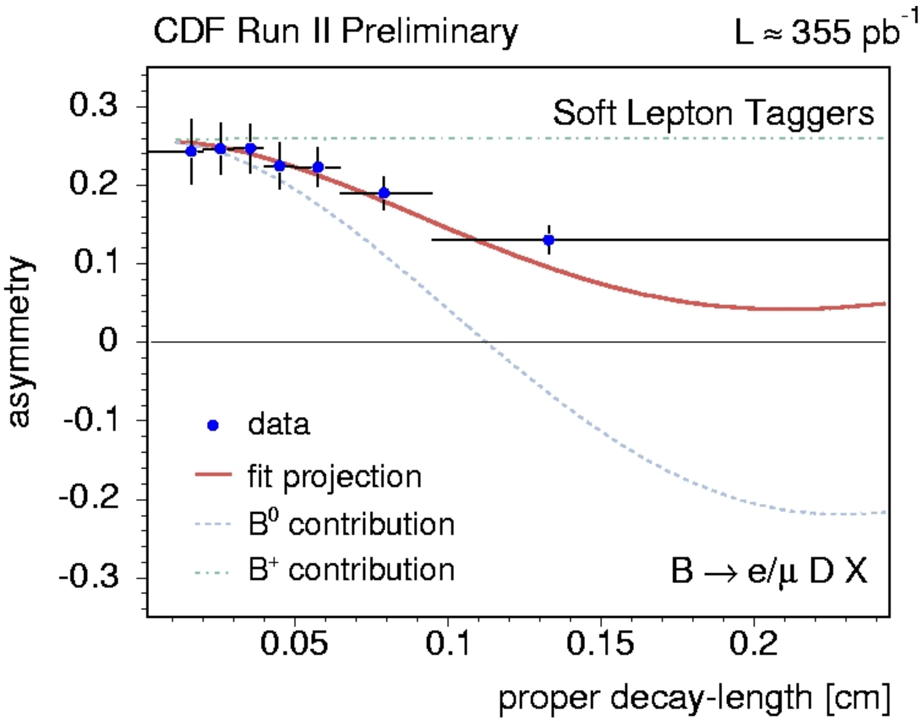
Initial State Flavor Tagging



Two techniques used:

- Opposite Side Tag
  - QCD produces $b\bar{b}$ pairs
  - Look for decay products of the *other* B hadron (eg, leptons)
  - Combined effectiveness: $\varepsilon D^2 = 1.5\%$
- Same Side Tag

Cross Checks with $B^0/B^{\pm}$



Δm_d=0.503±0.065 ps^{-1}
(hadronic)

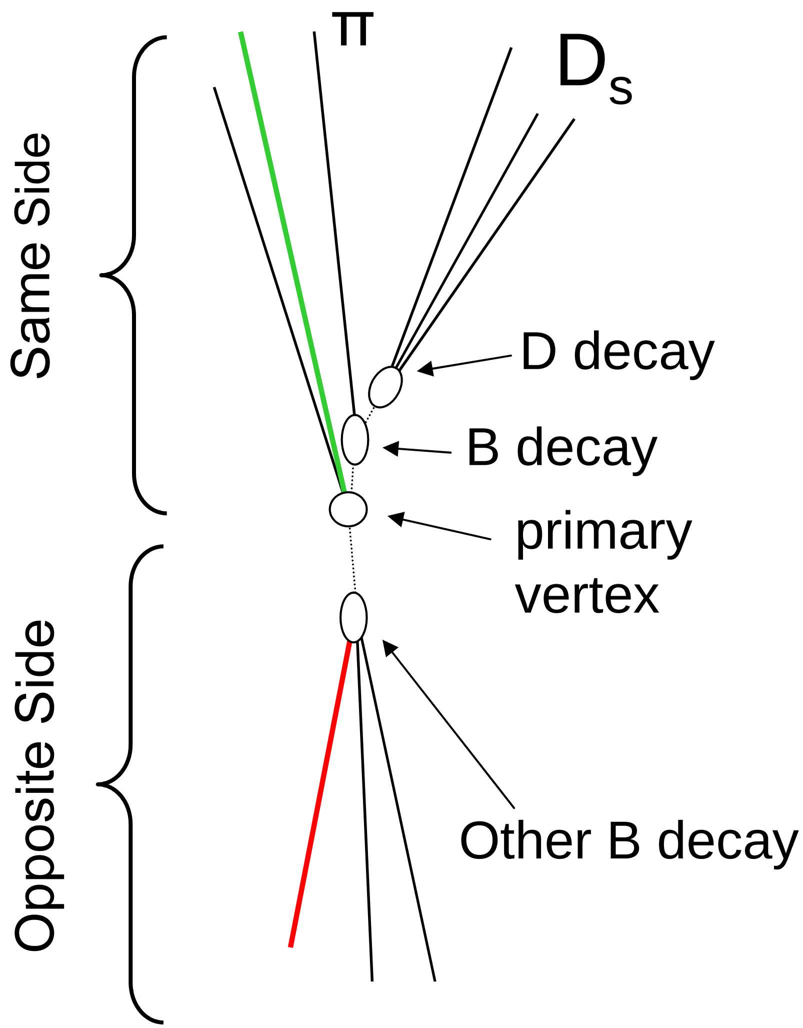
Δm_d=0.497±0.032 ps^{-1}
(semi-leptonic)

Δm_d=0.507±0.004 ps^{-1}
(World average)

$$\mathcal{P}_{mix}(t) \sim \frac{e^{-t/\tau}}{\tau}(1 - \mathcal{D}\cos(\Delta m_d t)) \rightarrow \frac{e^{-t/\tau}}{\tau}(1 - \mathcal{S}_{\mathcal{D}}\mathcal{D}\cos(\Delta m_d t))$$

- Account for any difference between signal and calibration samples.

Initial State Flavor Tagging



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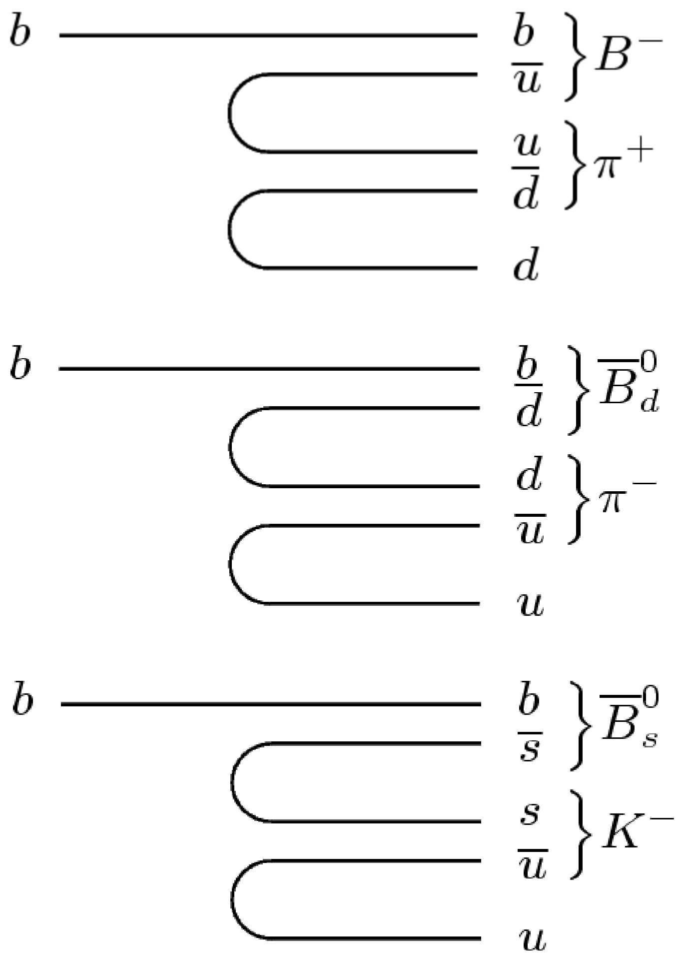
  - Look for particles produced in association with the B_s

Same Side Kaon Tag

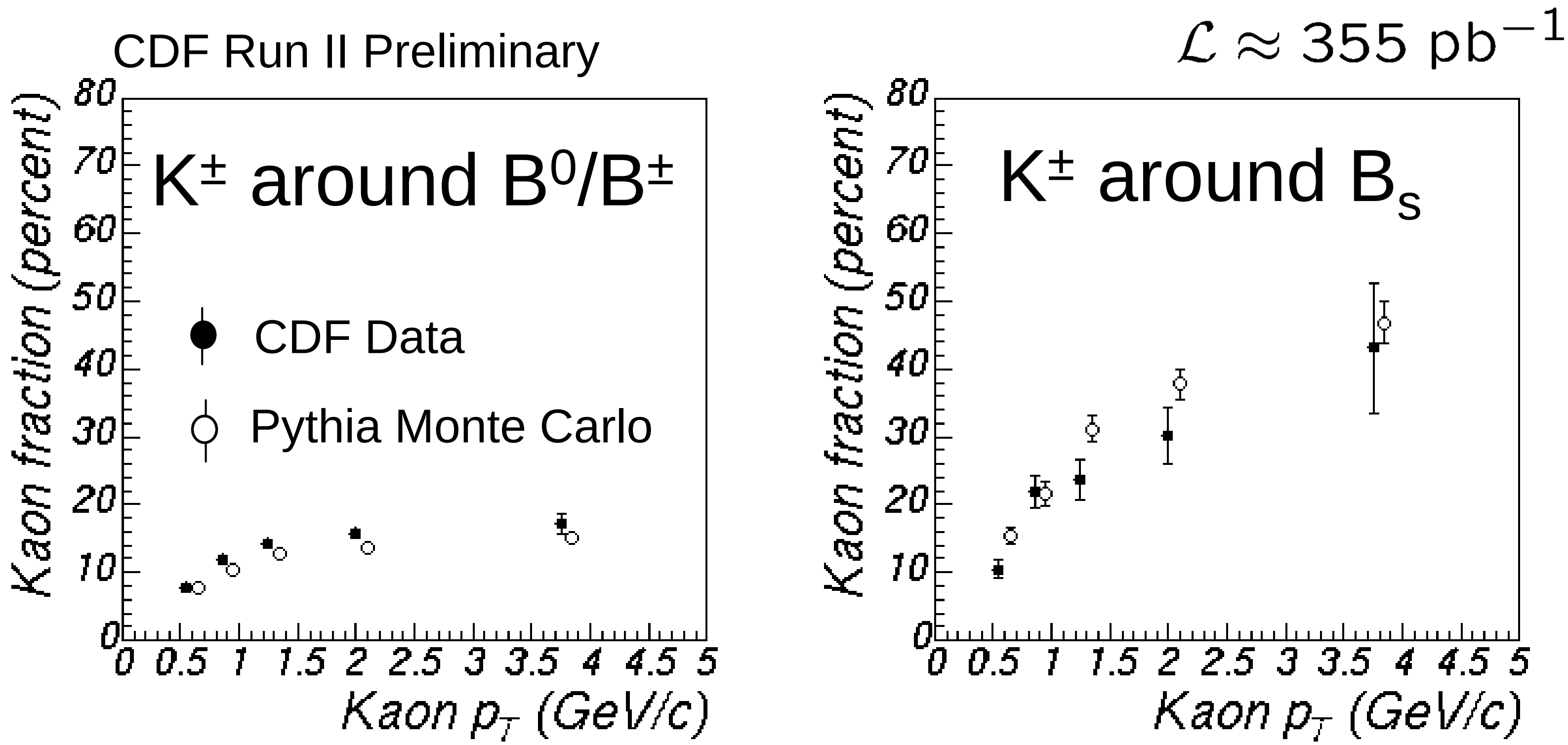


- Local quark flavor conservation in QCD
- Expect more kaons with B_s mesons
- Kaon charge identifies the initial B_s flavor
- *A primary motivation for building TOF detector.*

Original estimates based on Pythia (Lund string model): $\epsilon D^2 \sim 4\%$

Same Side Kaon Tag

- Count charged kaons around B^0, B^+, B_s:

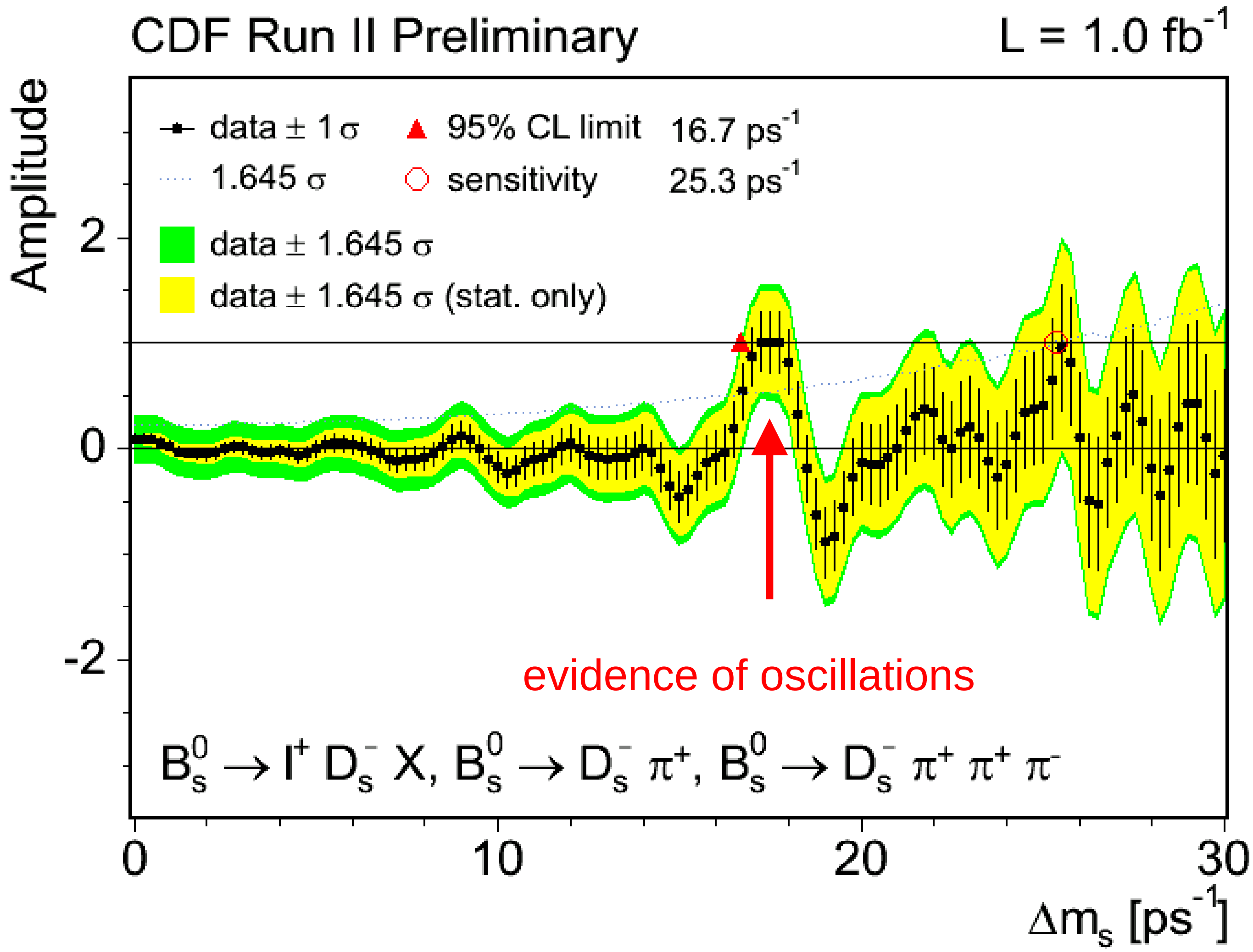


- Find more kaons produced in association with B_s
- Qualitative agreement with Monte Carlo

An Exciting Spring:

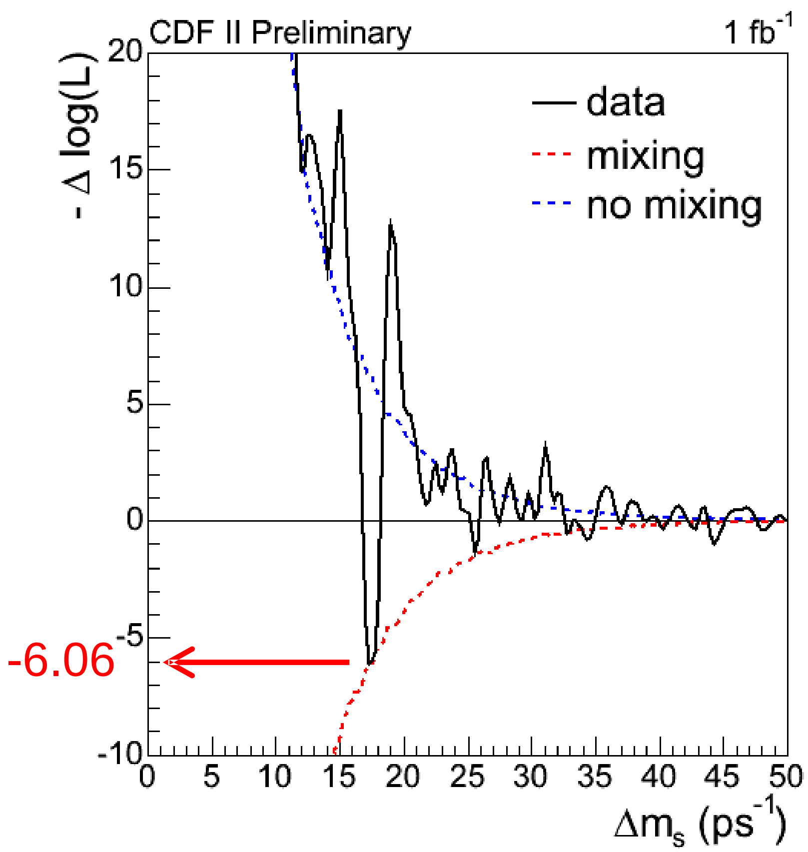
- March 12: DØ result released at Moriond
- March 14: CDF unblinded an analysis of about $^1/_3$ of the hadronic decay data
  - Observed evidence for oscillations
- Next few weeks:
  - Validation of remaining data
  - Inclusion of semi-leptonic analysis
  - Establish criteria for quoting a limit or a measurement

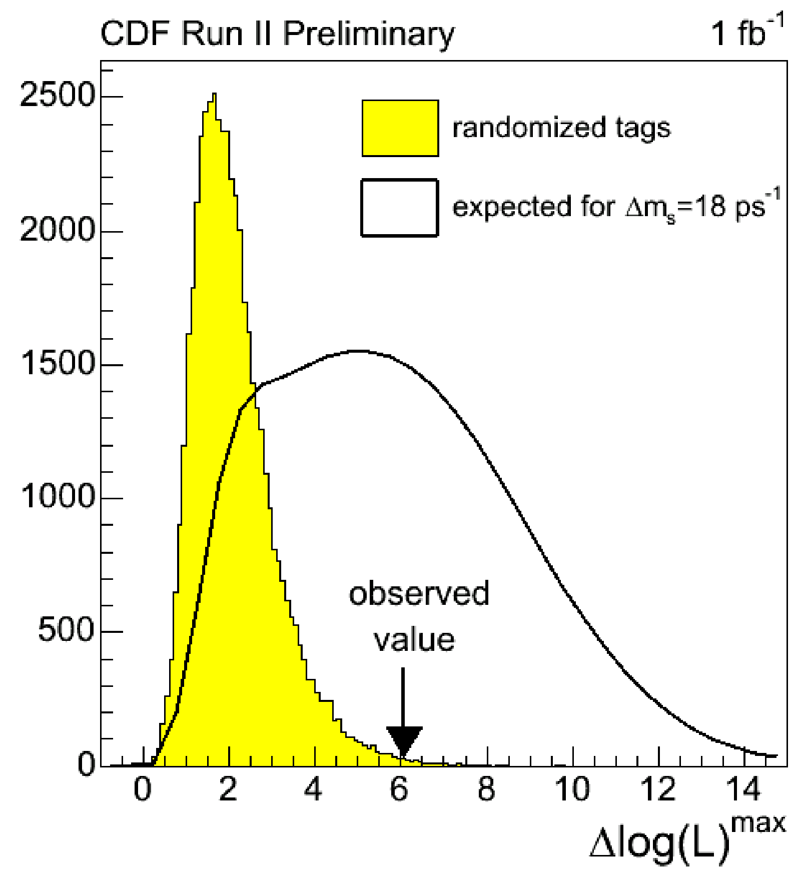
Unblinded CDF Analysis



Released April 11, presented at FPCP 2006 on April 12.

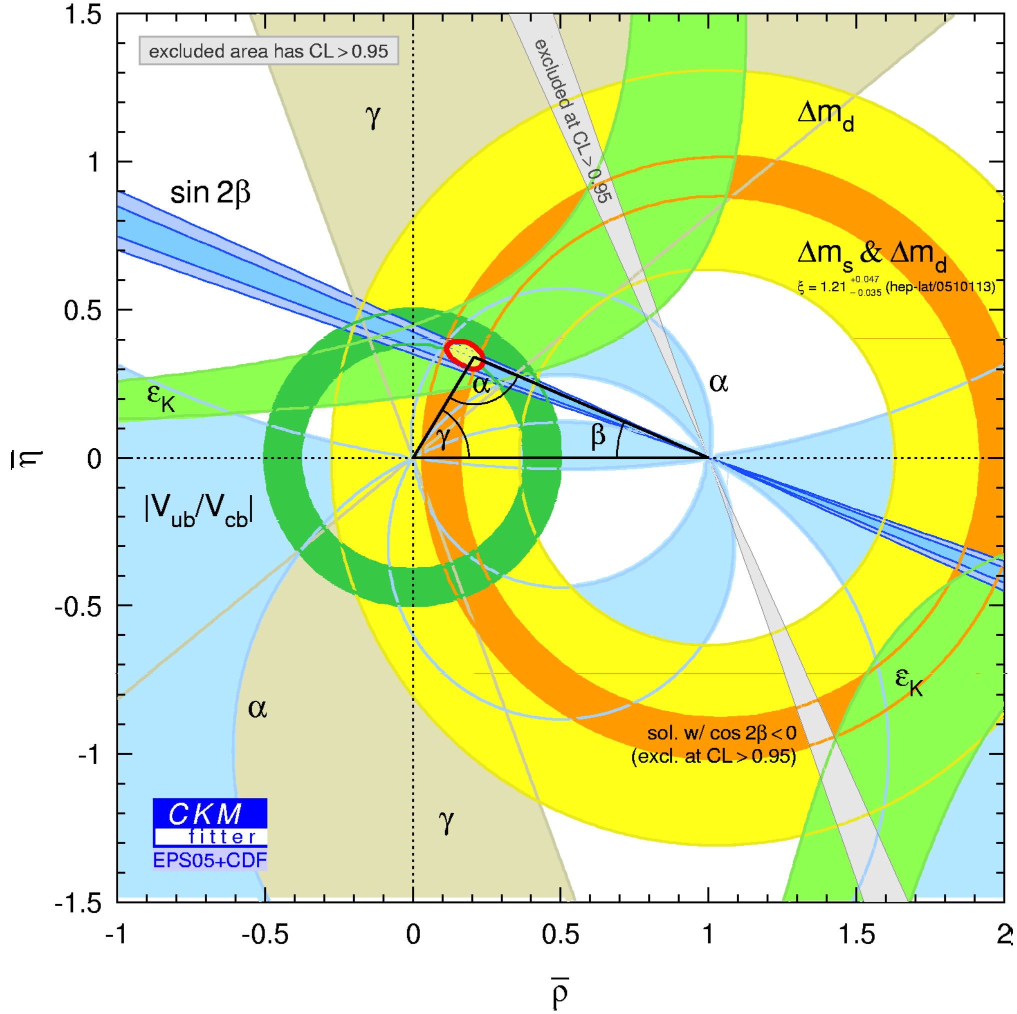
Limit or Measurement?





- Probability of statistical fluctuation: 0.5%
- Measure $\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07\ \mathrm{ps}^{-1}$

Constraints on CKM matrix



$$|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.007}$$

Future Prospects

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1}$$

$$\Delta m_d = 0.502 \pm 0.007 \text{ ps}^{-1}$$

- Already limited by input from Lattice QCD

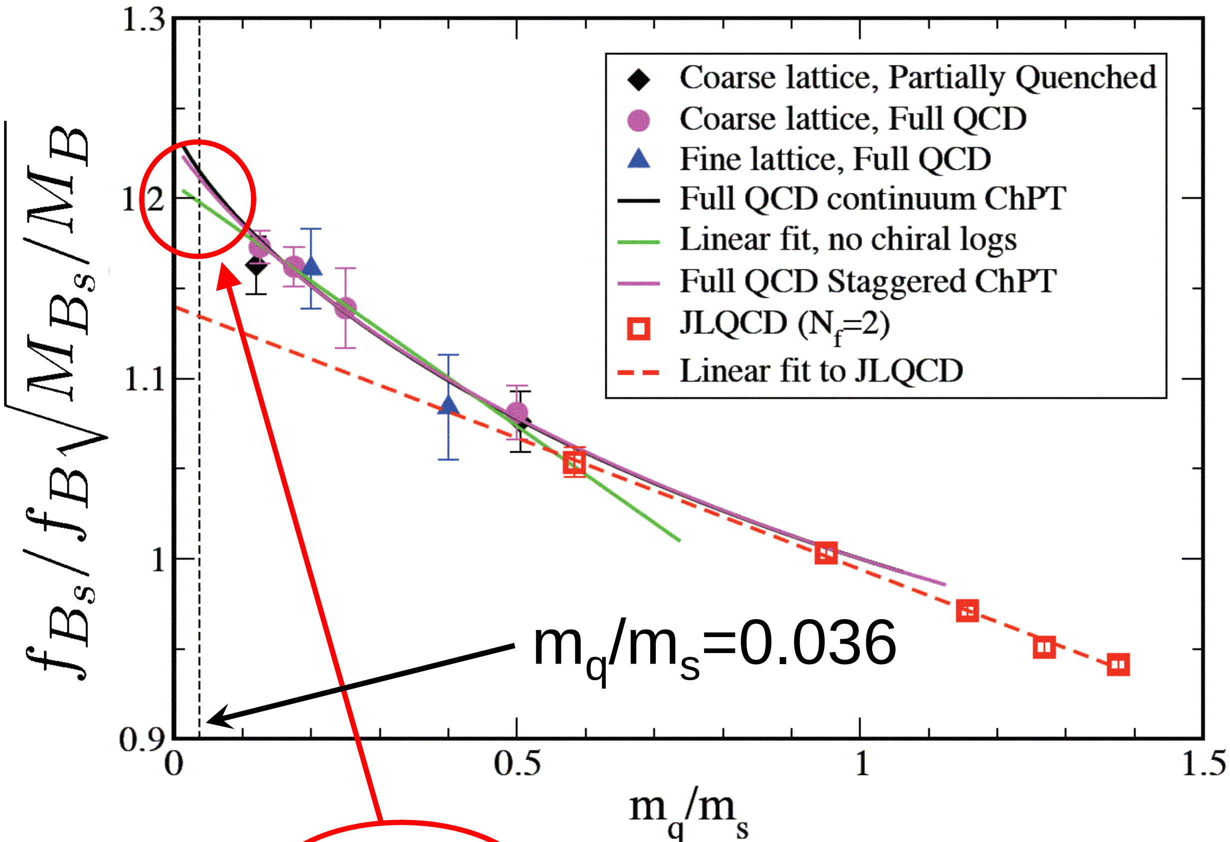
$$\xi = \frac{f_{B_s}}{f_{B_d}} \sqrt{\frac{B_{B_s}}{B_{B_d}}} = 1.210^{+0.047}_{-0.035} \qquad (3.8\%)$$

$$\frac{B_{B_s}}{B_{B_d}} = 1.017 \pm 0.016^{+0.056}_{-0.017}$$

From JLQCD Collab. ([hep-ph/0307039](hep-ph/0307039))

- Contributes 2.9% to ξ

Lattice Input from HPQCD+MILC



hep-lat/0507015

$$f_{B_s}/f_B = 1.20 \pm \underbrace{0.03}_{\text{Statistical uncertainty and extrapolation to small } m_q/m_s} \pm \underbrace{0.01}_{\text{All other uncertainties}}$$

Constraints on New Physics

$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1} \text{ (CDF)}$$

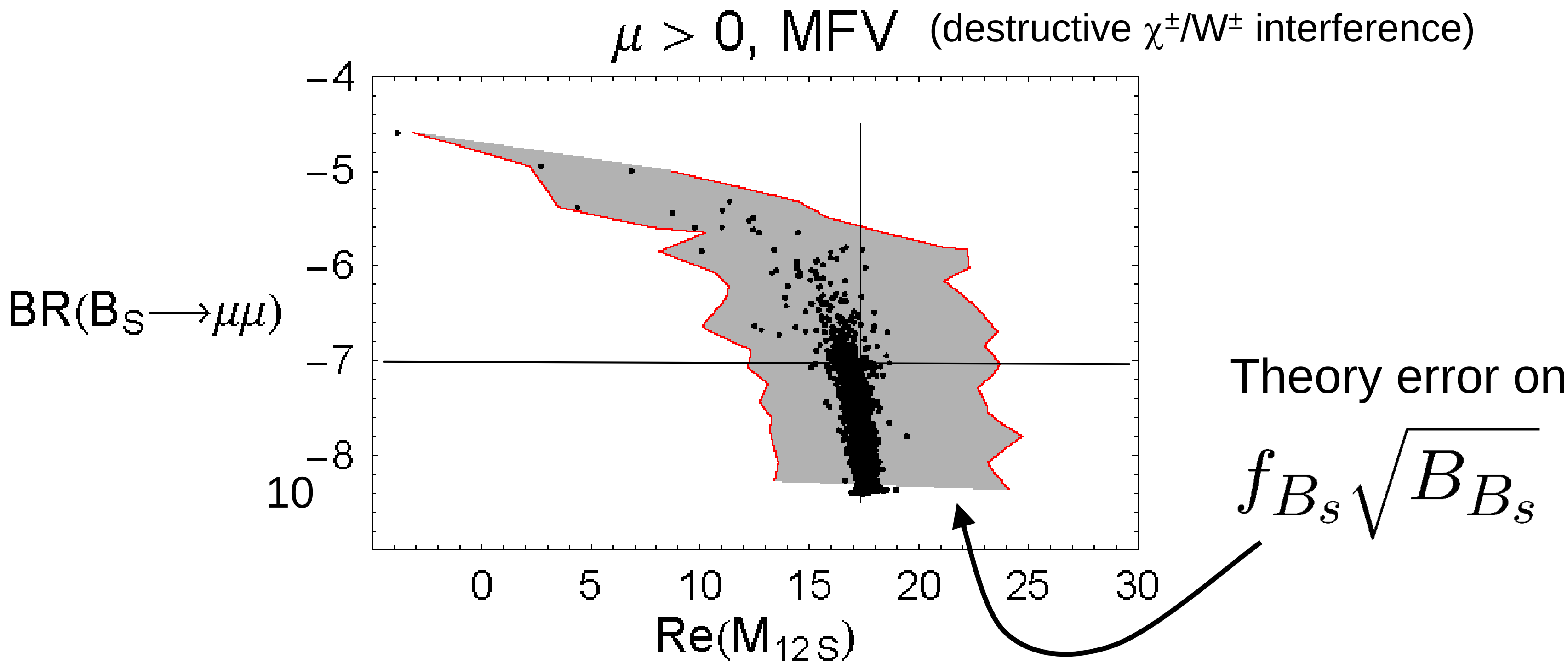
$$\Delta m_s = \begin{cases} 21.7^{+5.9}_{-4.2} \text{ ps}^{-1} & \text{(CKMFitter)} \\ 21.5 \pm 2.6 \text{ ps}^{-1} & \text{(UTFit)} \end{cases}$$

- Several different assumptions about flavor structure of SUSY models
  - Parameters in some models are constrained
  - Others are not...
- Correlated with other experimental results on FCNC $(B \to X_s\gamma,\ B_s^0 \to \mu^+\mu^-,\ \ldots)$

Example: Impact on MFV Scenarios

$$\mathrm{Br}(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7} \text{ @95\% C.L.}$$

(2006 CDF result)



Lunghi, Porod, Vives: hep-ph/0605177

Summary

$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1}$$

$$|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.007}$$

- Unlikely to be a statistical fluctuation
- Next improvements from lattice results...
  $f_{D^+}/f_{D_s^+}$ measured to few % at CLEO-c and BES-III
- Long term future uncertainty: ~1%?
- *A milestone has been reached in the world-wide heavy flavor physics program!*
  - *But there are still many more*